Satellites a further 2° away on both sides would result in the aggregate interference in the IRIDIUM downlink being a total of 2.5 dB above that of the "single-entry" value discussed above.

This may or may not be acceptable. If it is not, it can be avoided through the complementary use of the APC power reserve in the IRIDIUM satellite. If such a course is followed, the necessary separation angle is reduced from 0.92° to 0.44°, as discussed above in Section 4.2. In that case the increase in aggregate interference due to one neighbouring satellite is 0.51 dB. The presence of an additional two GSO satellites, one on either side a further 2° away, would increase the aggregate interference to 0.72 dB above the single-entry interference level. Further satellites at 2° intervals increase this level by very small amounts. Given that there is a 3 dB margin included in the IRIDIUM downlink budget for rare circumstances such as this, it would seem that

> *if the IRIDIUM system uses the APC power reserve in the downlink as well as the uplink, the presence of a string of satellites along the GSO at 2° spacing would reduce the C / (N+I) of the IRIDIUM system from about 10.7 dB to about 10.0 dB. Thus use of APC in both the uplink and downlink would enable the IRIDIUM system to operate in the presence of a series of satellites along the GSO.*

5.3 The Use of IRIDIUM APC Reserve Power for Both Interference Mitigation and Rain Attenuation

The large reserve power margins in the IRIDIUM system were implemented to accommodate variations in free-space losses due to range variations, and to increases in atmospheric attenuation due to relatively rare events in which there is heavy rain. This paper indicates how that same power reserve can be used for interference mitigation.

Let us considering the first of these three factors, use of power reserve to accommodate differences in free-space loss. When the SPACEWAY system is to serve CONUS the minimum elevation angle of earth stations of either system during a possible interference "hit" is about 30°. In contrast, the IRIDIUM system has a power margin to accommodate elevation angles down to 5°. Thus when considering simultaneous use of the power reserve for all three purposes, 20 Log { Sin(30)/Sin(5)}or about 15.2 dB is not required to accommodate free-space loss, and so is available temporarily for interference mitigation.

Considering now the second factor, rain attenuation, the same elevation-angle variation comes into play. During heavy rain the attenuation in dB is approximately proportional to the length of the propagation path through the atmosphere. The same 15.2 dB variation in path length comes into play at this point. Thus in combination, much less power reserve is required for these two effects at 30° as is required at the minimum 5°.

The third significant factor in this consideration is that the probability of a simultaneous interference "hit" requiring the utilization of the power reserve, and of a heavy rain event also requiring the use of that same power reserve, is very low. A possible interference hit and a heavy rain attenuation event are statistically independent events, there is no causal relation between them. This their joint probability is a product of their individual probabilities; the relation

$$P(x,y) = P(x) * P(y) \quad \text{.......} \quad (3)$$

applies.

The probability of a potential interference hit into the IRIDIUM system, even without any interference mitigation measure except the antenna discrimination of the SPACEWAY earth terminal antennas, is only 0.06. [1]. When this factor is combined with the partial amount of reserve power available for rain attenuation due to the interference hit event occurring at an elevation angle not less than 30°, the probability of a simultaneous interference hit and heavy rain attenuation that cannot be accommodated by the available power reserve is not expected to exceed the acceptable outage probabilities indicated in [2].

Thus, in conclusion, it is expected that when the SPACEWAY system is used to provide service in CONUS the occurrence of heavy rain attenuation is expected to be able to be accommodated even though the IRIDIUM power margins are also utilized to alleviate the effects of rain attenuation.

5.4 Interference Criteria Used in the Analysis

When very little is known about two satellite networks that might share the use of a block of radio spectrum, it is customary to use $\Delta T / T$ or I_0/N_0 as a measure of their shareability. However, when considerable information is known about both networks, as is the case concerning the knowledge of the characteristics here of SPACEWAY and IRIDIUM, is more accurate to use that detailed information fully. In doing so it has been generally found to be useful to use either the post-detection ratio S/(N+I) or the pre-detection ratio C/(N+I) as a measure of the shareability of the two networks. In the present case both networks are digital in nature, so the post-detection factor E_b/N_0 is an accurate measure of the performance of the networks. This factor is closely related to the pre-detection C/(N+I) over the full band of the system involved, the only difference being the ratio between signal bandwidth and data rate. Thus C/(N+I) is used in this analysis.

Turning now to the levels of interference, or the values of C/(N+I) that would constitute harmful interference, the situation here is one in which both networks have large margins to accommodate transient interference events, and in all cases these events are transitory in nature. Moreover, they are statistically independent events, both with low probabilities of occurrence, so their joint probabilities are extremely low. The approach taken, then, is to ensure that for each of the events there is a reasonable margin of performance still available after the interference or attenuation event is accommodated. In this analysis that residual margin is 3 dB.

This approach results in some cases of the expected interference being quite large in comparison with the clear-sky thermal noise level of the networks. However, that is irrelevant. Both networks have large margins available, up to 34 dB in the case of the IRIDIUM uplink. It is quite appropriate to use this available system characteristic to seek measures in which both systems can use the radio spectrum efficiently. That is done here. The result is what may seem on initial consideration to be rather high transient I_0/N_0 values. However, that is quite appropriate for 30/20 GHz systems with high margins available. In fact, it is necessary if the available spectrum is to be used efficiently.

5.5 Usefulness of the Site Diversity Mitigation Measure at Low Elevation Angles

The ease in using the site-diversity interference-mitigation measure is greatest when the elevation angles of the GSO satellites that are involved are large. The reasons for that conclusion are as follows:

1. the necessary discrimination angles of the IRIDIUM earth station antenna to make the measure effective, varying from 0.313° to 0.92° as described above in various circumstances, is independent of the GSO satellite's elevation angle;

2. a potential interference "hit" occurs only when the non-GSO satellite is at the same location, ie. the same azimuth and elevation angles, as seen by the earth station antennas of both systems;

3. the distance from the earth stations to the LEO satellite, and so the required separation distance on the ground between the two earth stations involved, varies as $\{ \sin(\theta)\}^{-1}$, where θ is the satellite elevation angle.

4. if the two IRIDIUM earth stations involved are in a worst-case alignment with respect to the azimuth of the satellites, ie. in the plane defined by the earth stations, the satellites, and the centre of the Earth, then another $\{ \sin(\theta)\}^{-1}$ factor must be included, making the worst-case or largest necessary distance between the IRIDIUM earth stations involved proportional to $\{ \sin(\theta)\}^{-2}$.

In the above analysis involving the SPACEWAY to serve CONUS, θ_{min} was set at 30°, resulting in a factor of 4 in determining the necessary worst-case minimum distance between the earth stations.

At very low elevation angles not involving a SPACEWAY-CONUS system, at say 10°, this factor would increase to 33, resulting in perhaps impractical earth-station separations. However, this observation should be tempered with two other observations:

1. Ka-band GSO systems tend to operate at high angles of elevation wherever possible, compared with practice at C-band or even Ku-band, because of the need to add significant power margins of Ka-band systems at low elevation angle ;

2. finding GSO orbit locations with high elevation angle may be easier than at lower frequency bands, because of the significant space-station antenna selectivity at these bands, and therefore the ability to coordinate systems at similar orbit locations when they serve different areas.

These factors tend to result in Ka-band fixed-satellite systems having low elevation angles mainly in higher latitude areas. At higher latitudes, where the earth station site diversity becomes less attractive because of the $\{ \mathrm{Sin}(\theta)\}^{-2}$ factor in the necessary earth station separation distances, this interference-mitigation technique can be replaced in a completely complementary manner with a space-station diversity technique described in detail in Reference [1].

If the satellite is at approximately the same longitude as its service area, earth-station site diversity is an effective interference-mitigation tool at latitudes as high as the 50° to perhaps the 55° range, where elevation angles not less than 25° to 30° can be expected. At those latitudes and above, space station diversity becomes a very effective interference mitigation technique, without requiring the addition of any additional IRIDIUM spacecraft in its constellation of 66. Thus the two techniques complement each other very well: earth-station site diversity at low to medium latitudes, and space-station diversity at higher latitudes. Alaska, for instance, is an ideal location to implement space-station diversity to alleviate the interference discussed in this paper.

6. Conclusion

Earth station site diversity is seen in this paper as a powerful technique that can be used to enable the SPACEWAY system and the feeder links of the IRIDIUM system to be able to share the same portions of Ka-band. It requires the three earth stations of an IRIDIUM earth-station complex to be used in a judicious manner to avoid the incidence of interference "hits". This use can be scheduled well in advance of the time that it is applied. The technique also requires the utilization of APC power margins in the IRIDIUM system, particularly that available in current designs of IRIDIUM earth stations. The technique is able to accommodate the eventuality of a heavily-use GSO, and can simultaneously provide limited but adequate protection against rain attenuation.

At higher latitudes, the technique can be replaced by space-station diversity of the IRIDIUM satellites, again on a scheduled basis and without requiring the addition of any additional IRIDIUM spacecraft.

Interference levels in both systems are high when compared with classical steady-state interference levels in GSO satellite networks at lower frequency bands. However, at all times the pre-detection carrier to noise plus interference levels, or equivalently the energy per bit divided by the noise spectral density in the detector of the digital signals, is in the order of 3 dB above their minimum required values. Thus the technique is seen as a way of enabling high utilization of Ka-band spectrum and at the same time enabling high performance of both networks during transient interference events.

References

1. Report for Hughes Space and Communications Company by Robert Bowen Associates Ltd, " Analysis of the Feasibility of Sharing Co-Directional Use of the Fixed-Satellite 19 GHz Downlink and 29 GHz Uplink Bands Between the Geostationary SPACEWAY Fixed-Satellite System and Feeder Links of the IRIDIUM LEO Mobile-Satellite System", March 8, 1995.

2. Information Paper, " Mitigation of transient interference between 20/30 GHz GSO/FSS networks and Non-GSO Feeder Links for MSS Operating in the 1-3 GHz Frequency Bands", Ken Engle, August 16, 1995.

Annex A

System Characteristics
Used in Interference Analysis
Between Spaceway and Iridium Systems

A.1: Introduction

Characteristics of the SPACEWAY and IRIDIUM systems that are used in determining the noise and interference levels in the two systyems are described in this annex. The characteristics are first used in analyses of the link budgets of the SPACEWAY and IRIDIUM systems, and the information obtained in those analyses are in turn used in the analysis of interference between the two systems. Thus the data listed in this annex is the data-base for the analysis throughout the paper. Changes in numerical values of the quantities discussed in this annex would not necessarily affect the analysis process, but would affect the numerical values of the results obtained, and so might affect the conclusions drawn.

A.2: Characteristics of the Iridium System

A.2.1 Iridium Uplink Characteristics:

Iridium Uplink System Characteristics:

Modulation:	QPSK / 6.250 Mbps raw data rate, 3.125 Mbps information rate
Bandwidth:	6.250 MHz (one bit per Hz before a 2:1 coding redundancy)
Polarization:	Right-hand circular
C/(N+I), rain	7.8 dB
C/(N+I), clear	10.7 dB
Req'd. C/(N+I)	7.7 dB, assumed to be a separate requirement for uplink and downlink independently, with re-modulation in spacecraft such that bit errors, not noise powers, add in considering total signal path. For Iridium the bit-rate and signal bandwidth are equal, and so $E_b / N_o = C / N$.

Iridium Uplink Satellite Characteristics:

Min. Elev. Angle:	5°
Satellite Altitude:	780 km.
Sat. Noise Temp.	1,295 ° K
Sat. Ant. Gain:	30.1 dBi, 5 ° beamwidth, sidelobes as per App.29 Ann. III
Sat. Ant. Char.	4 independent steerable spot beams per spacecraft

Iridium Uplink Earth Station Characteristics:

ES Antenna Gain:	56.3 dBi, 0.24° beamwidth, steerable
Xmtr. Power:	-22.3 dBW to + 12 dBW, APC capability over the 34.3 dB range, designed to overcome range and atmospheric losses, to keep constant Eb/(No + Io) at the receiver's antenna input

A.2.2 Iridium Downlink Characteristics:

Iridium Downlink System Characteristics: (same as for the uplink):

Modulation:	QPSK / 6.250 Mbps raw data rate, 3.125 Mbps information rate
Bandwidth:	6.250 MHz (one bit per Hz before a 2:1 coding redundancy)
Polarization:	Right-hand circular
C/(N+I), rain	7.8 dB
C/(N+I), clear	10.7 dB
Req'd. C/(N+I)	7.7 dB, assumed to be a separate requirement for uplink and downlink independently, with re-modulation in spacecraft such that bit errors, not noise powers, add in considering total signal path. For Iridium the bit-rate and signal bandwidth are equal, and so for Iridium

$$E_b / N_o = C / N.$$

Iridium Downlink Earth Station Characteristics:

ES Antenna Gain:	53.2 dBi, 0.36° beamwidth, steerable
Noise Temp.	731° K

Iridium Downlink Satellite Characteristics:

Satellite Altitude:	780 km.
Sat. Ant. Gain:	26.9 dBi, 7.4 ° beamwidth, sidelobes as per App.29 Ann. III
Sat. Ant. Char.	4 independent steerable spot beams per spacecraft
Xmtr. Power:	-22.4 dBW to -3.2 dBW, APC capability over the 19.2 dB range, designed to overcome range and atmospheric losses, to keep constant $E_b/(N_o + I_o)$ at the receiver's antenna input

A.2.3 Iridium Earth Station Antenna Characteristics:

Important characteristic of the IRIDIUM system considered in Section 4 of the paper are the sidelobe characteristics of its earth station's antenna. These characteristics are important in that they lead to determination of the necessary angular mispointing of that antenna to achieve enough isolation betweeen the IRIDIUM and SPACEWAY systems, and so the separation on the ground between two earth stations used in a site-diversity mode of operation.

The main beam of the IRIDIUM feeder-link antenna can be modelled by the relations

$$G(\phi) = G_{max} - 2.5 * 10^{-3} (D/\lambda)^2 \phi^2$$

$$= G_{max} - K\phi^2 \quad , \text{for } 0 \le \phi \le \phi_m \quad \text{(A.1)},$$

$$= G_1 \quad , \text{for } \phi_m \le \phi \le \phi_r \quad \text{(A.2)},$$

and

$$= 32 - 25 \text{ Log}(\phi) \quad , \text{for } \phi_r \le \phi \le 48° \quad \text{(A.3)},$$

based on the antenna pattern in Annex II of Appendix 28 of the Radio regulations. The first sidelobe gain G_1 is determined by the relation

$$G_1 = 2 + 15 \text{ Log}(D/\lambda) \quad \text{(A.4)}.$$

The angles ϕ_m and ϕ_r are specified by the relations

$$\phi_m = 20 (D/\lambda)^{-1} \{ G_{max} - G_1 \}^{0.5} \quad \text{(A.5)},$$

and

$$\phi_r = 15.85 \ (D/\lambda)^{-0.6} \quad \text{(A.6)}.$$

The antenna's equivalent (D/λ) in the above relations can be estimated from its maximum gain by the relation

$$20 \text{ Log}(D/\lambda) = G_{max} - 7.7 \text{ dB} \quad \text{(A.7)}.$$

The IRIDIUM Earth station antenna has a boresite gain of 56.3 dBi in the uplink and 53.2 dBi in the downlink. From Eq'n (A.7) those Earth stations have a (D/λ) of 270 in the uplink and 188 in the downlink. This and the other antenna pattern parameters are given in Table A.1 for both uplink and downlink.

Table A.1
IRIDIUM Earth Station Antenna Characteristics

Parameter	Uplink Value	Downlink Value
G_{max}	56.3 dBi	53.2 dBi
D / λ	270	188
G_1	38.5 dBi	36.1 dBi
ϕ_m	0.313°	0.440°
ϕ_r	0.55°	0.68°

These values are used in Equations (A.1) to (A.6) above to determine the required value ϕ_S to achieve isolation of the two networks through IRIDIUM Earth station antenna diversity.

It is noted that FCC Regulation 25.209 indicates an off-boresite antenna-gain 3 dB below that of Equation (D.7c) for off-boresite angles between 1° and 9.2°. However, the tighter constraints apply only to angles in the directionof the GSO. Since the IRIDIUM Earth-station antenna would have to operate in any combination of azimuth and elevation angle, it is concluded that the tighter constraints in the FCC's 25.209 do not apply, and so Equation (A.3) is used for all angles ϕ in the range $\phi_r \leq \phi \leq 48°$.

A.3: Characteristics of the Spaceway System

A.3.1 Spaceway Uplink Characteristics:

Spaceway Uplink System Characteristics:

Modulation:	QPSK / 1544, 768, 384 kbps
Access:	FDMA
Bandwidth:	2 MHz, 1 MHz, or 0.500 MHz, (0.77 bits per Hz)
Polarization:	Circular
$E_b/(N_o)$, rain	9.7 dB
C / N, rain	8.6 dB, reduced from $E_b / (N_o)$ by 1.1 dB
$E_b/(N_o)$, clear	11.7 dB
C / N, clear	10.6 dB, reduced from $E_b / (N_o)$ by 1.1 dB
Req'd $E_b/(N_o + I_o)$	8.0 dB, and
Req'd. C/(N+I)	6.9 dB, reduced from $E_b/(N_o)$ by 1.1 dB, with re-modulation in spacecraft such that bit errors, not noise powers, add in considering total signal path.

Spaceway Uplink Earth Station Characteristics:

ES Antenna Gain:	44.3 dBi, 1.1° beamwidth, not steerable
Xmtr. Power:	-3.5 dBW for the 384 kbps carrier

Spaceway Uplink Satellite Characteristics:

Min. Elev. Angle:	30 °
Satellite Altitude:	GSO.
Sat. Noise Temp.	575 ° K
Sat. Ant. Gain:	46.5 dBi, 1 ° beamwidth, sidelobes as per App.29 Ann. III
Sat. Ant. Char.	multiple simultaneously-used spot beams per spacecraft, not steerable

A.3.2 Spaceway Downlink Characteristics:

Spaceway Downlink System Characteristics :

Modulation:	QPSK / 92 Mbps
Bandwidth:	120 MHz (0.77 bit per Hz)
Polarization:	Circular
$E_b/(N_o + I_o)$, rain	5.7 dB
C/(N+I), rain	4.6 dB, reduced from $E_b/(N_o)$ by 1.1 dB
$E_b/(N_o + I_o)$, clear	17.9 dB
C/(N+I), clear	16.8 dB, reduced from $E_b/(N_o)$ by 1.1 dB
Req'd. $E_b/(N_o + I_o)$	5.0 dB, with re-modulation in spacecraft such that bit errors, not noise powers, add in considering total signal path,
Req'd. C/(N+I)	3.9 dB, reduced from $E_b/(N_o)$ by 1.1 dB, with re-modulation in spacecraft such that bit errors, not noise powers, add in considering total signal path.

Spaceway Downlink Earth Station Characteristics:

ES Antenna Gain:	43.1 dBi, 1.6° beamwidth, not steerable
Noise Temp.	275 ° K

Spaceway Downlink Satellite Characteristics:

Min. Elev. Angle:	30 °
Satellite Altitude:	GSO.
Sat. Ant. Gain:	46.5 dBi, 1.1 ° beamwidth, sidelobes as per App.29 Ann. III
Sat. Ant. Char.	multiple simultaneously-used spot beams per spacecraft, not steerable
Xmtr. Power:	12.5 dBW

Annex B

Noise Budgets of the IRIDIUM and SPACEWAY Systems

B.1 Introduction

The noise budgets of the IRIDIUM and SPACEWAY systems are analyzed in this annex, based primarily on information available in Annex A of this paper. This analysis is done primarily to provide the necessary input data for an analysis of the interference between the two systems. Particular attention is paid to the automatic power control (APC) of the Iridium system, as its use is important in determining the interference between the two systems, as is discussed in the main report and in Annex C to follow. In this consideration of the Iridium APC system no account is taken of the quantization of the APC steps nor of inaccuracies in the APC servo system.

B.2. IRIDIUM System Noise Budgets

B.1.1 The IRIDIUM Uplink Noise Budget

The Iridium uplink noise budget is a function of the elevation angle of the Iridium spacecraft. Elevation angles of 90° (zenith) , 30°, and 5° are considered here. 30° is important because it is the minimum operational angle of the Spaceway system, and 5° because it is the minimum operational angle of the Iridium system. The Iridium uplink parameters are indicated in Table B-1, using the standard satellite link equations. The clear-air attenuation is determined from formulae in CCIR Report 564-4 (1990). Simplified high-angle formulae of that report are used, because we are particularly interested in the budgets in the elevation angle range near 30 °, the minimum angle of an earth station antenna of the SPACEWAY system in CONUS and so the minimum elevation angle at which there would be significant interference between the two networks.

B.1.2 The IRIDIUM Downlink Noise Budget

The same process is repeated for the Iridium downlink, concentrating on elevation angles of 90° (zenith) , 30°, and 5°. The Iridium downlink parameters are indicated in Table B-2. There seems to be some lack of rain-attenuation margin or even clear-air-attenuation margin in the Iridium downlink budget at low elevation angles, but this is not of particular concern as the interference events will occur at elevation angles of 30° and greater. Further, the low margins may be because of the use of multiple earth stations and the placement of earth-station complexes in dry climatic locations. In any case, these numbers affect the present study only to the extent that they relate to the understanding of the operation of the Iridium APC system in an interference environment.

Table B-1

Uplink Noise Budgets of the Iridium System at Spacecraft Elevation Angles 90 °, 30 °, and 5 °

Satellite Elevation Angle	90°	30°	5°
Carrier Frequency, GHz	29.3	29.3	29.3
Satellite Noise Temperature, Degrees K	1,295	1,295	1,295
Signal Bandwidth, MHz	6.25	6.25	6.25
Channel Separation, MHz	7.67	7.67	7.67
Noise Power, dBW	-129.5	-129.5	-129.5
Req'd. Clear Air C = N + 10.7 dBW	-118.8	-118.8	-118.8
Path Length, km.	780	1,560	8,950
Free Space Loss, dB	179.7	185.7	200.9
Earth Station Antenna Gain, dBi	56.3	56.3	56.3
Space Station Antenna Gain, dBi	30.1	30.1	30.1
Clear Air Attenuation, dB	0.41	0.83	4.76
Tx Power in dBW to provide C/N = 10.7 dB	-25.1	-18.7	+0.5
Margin of APC Tx. with Pmax = +12 dBW	37.1	30.7	11.5

Table B-2

Downlink Noise Budgets of the Iridium System at Spacecraft Elevation Angles 90 °, 30 °, and 5 °

Satellite Elevation Angle	90°	30°	5°
Carrier Frequency, GHz	19.6	19.6	19.6
Earth Stat'n Noise Temperature, Degrees K	731	731	731
Signal Bandwidth, MHz	6.25	6.25	6.25
Channel Separation, MHz	7.22	7.22	7.22
Noise Power, dBW	-132.0	-132.0	-132.0
Req'd. Clear Air C = N + 10.7 dBW	-121.3	-121.3	-121.3
Path Length, km.	780	1,560	8,950
Free Space Loss, dB	176.2	182.2	197.4
Earth Station Antenna Gain, dBi	53.2	53.2	53.2
Space Station Antenna Gain, dBi	26.9	26.9	26.9
Clear Air Attenuation, dB	0.43	0.85	4.88
Tx Power in dBW to provide C/N = 10.7 dB	-24.8	-18.3	+ 0.9
Margin of APC Tx. with Pmax = - 3.2 dBW	21.6	15.1	(-)

B.2 The Spaceway Noise Budgets

The budgets of the SPACEWAY system are simpler than those of the Iridium systems, as there is no wide variance in system elevation angles, nor is there the use of APC in the many small user earth terminals that there is in the large Iridium feeder link earth stations.

The uplink budget of the Spaceway system is indicated in Table B-3, and the downlink budget is in Table B-4.

Table B-3

Uplink Noise Budget of the Spaceway System at a Spacecraft Elevation Angle of 30 °

Carrier Frequency, GHz	29.3
Satellite Noise Temperature, Degrees K	575
Signal Bandwidth, kHz	500
Channel Separation, kHz	500
Noise Power, dBW	-144.01
Uplink Transmitter Power, dBW	- 3.5
Earth Station Antenna Gain, dBi	44.3
Clear Air Attenuation, dB	0.8
Path Length, km.	39,230
Free Space Loss, dB	213.7
Space Station Antenna Gain, dBi	46.5
Clear-Air Received Signal Strength, dBW	- 127.2
Clear-Air C/N, dB	16.8
Required Uplink Clear-Air C / N, dB	10.6
Margin of Tx. with P = -3.5 dBW	6.2

Table B-4

Downlink Noise Budget of the Spaceway System at a Spacecraft Elevation Angle of 30 °

Carrier Frequency, GHz	19.6
Satellite Noise Temperature, Degrees K	275
Signal Bandwidth, MHz	120
Channel Separation, MHz	120
Noise Power, dBW	-123.4
Downlink Transmitter Power, dBW	+ 12.5
Earth Station Antenna Gain, dBi	43.1
Clear Air Attenuation, dB	0.8
Path Length, km.	39,230
Free Space Loss, dB	210.2
Space Station Antenna Gain, dBi	46.5
Clear-Air C, dBW	- 108.9
Clear-Air C/N, dB	14.5

Annex C

Worst-Case Interference Analyses

C.1 Introduction

"Worst-case" interference analysis is determined in this annex. "Worst-case interference analysis" is the analysis of interference into each of the systems in the worst-case situation, ie. in the situation in which the earth terminal involved is pointed directly at both the GSO SPACEWAY satellite and the LEO IRIDIUM satellite. This is a transient situation, in that the LEO satellite is only in the main beam of the GSO earth station antenna for a short period of time, and visa-versa. The transient nature of the interference is discussed elsewhere in the paper; in this annex only the peak interference levels of the transient interference burst are determined.

These peak transient interference levels are determined for four distinct interference situations:

1. interference from the GSO earth station into the LEO satellite;
2. interference from the LEO earth station into the GSO satellite;
3. interference from the GSO satellite into the LEO earth station; and
4. interference from the LEO satellite into the GSO earth station.

The analysis is done at a location where the elevation angles to the satellites is 30°, the minimum planned elevation angle of the SPACEWAY system. 384 kbps digital traffic is assumed in the SPACEWAY system from the user terminals.

C.2 Interference Ratios and the Equations Specifying their Magnitudes

In this analysis the pre-detection carrier-to-interference ratios C / I are determined, as discussed in Section 3.1 of the paper. These C / I ratios are related to the post-detection E_b / N_o ratios and so BER ratios by the differences in dB between C / I and E_b / N_o specified in the information contained in Annex A. The "minimum" C/(N+I) values specified in Annex A are considered to be interference thresholds; interference margins are determined by whether the interference is more or less than the values specified by those thresholds.

The interference equations in an uplink-interference situation are:

$$C = P_D - A_{CA} - A_{FS} + G_{DES} + G_{SC} \qquad \text{(C.1)},$$

$$I = P_I - A_{CA} - A_{FS} + G_{IES} + G_{SC} \qquad \text{(C.2)},$$

and

$$C/I = (P_D - P_I) + (G_{DES} - G_{IES}) + F_{BW} \qquad \text{(C.3)},$$

where C is the desired carrier level at the interfered-with satellite,

P_D is the transmitter power level of the desired carrier,

A_{CA} is the clear-air attenuation level in the transmission path,

A_{FS} is the free-space loss in the transmission path to the interfered-with satellite,

G_{DES} is the earth-station gain of the desired signal,

G_{SC} is the satellite-antenna gain of the interfered-with satellite,

I is the interfering carrier level at the interfered-with satellite,

P_I is the transmitter power level of the interfering carrier,

G_{IES} is the earth-station gain of the interfering signal, and

F_{BW} is a factor to account for the different bandwidths of the desired and interfering carriers.

It should be noted that in Equation (C.3) the terms A_{CA}, A_{FS}, and G_{SC} are not present, since they are common to the paths of the desired and the interfering carrier. (The desired and interfering earth stations are assumed to be at roughly the same location, relative to the distances of either of the two satellites.

Another point to clarify is that the interference is determined in clear-air propagation conditions; no account is taken of rain attenuation in these calculations. This is because a rain event and an interference event are statistically independent events, each with low probability of occurrence; the joint probability of the two events is therefore extremely low and so is ignored in this annex. The matter is discussed in more detail in Section 5 of the paper.

The interference equations in an downlink-interference situation are similar but slightly more complex. They are:

$$C = P_D - A_{CA} - A_{D,FS} + G_{DSC} + G_{DES} \qquad \text{(C.4)},$$

$$I = P_I - A_{CA} - A_{I,FS} + G_{ISC} + G_{DES} \qquad \text{(C.5)},$$

and

$$C/I = (P_D - P_I) + (G_{DSC} - G_{ISC}) + F_{BW} - (A_{D,FS} - A_{I,FS}) \qquad \text{(C.6)},$$

where most of the terms represent the same quantities as in the uplink equations, except that

$A_{D,FS}$ is the free-space-loss of the desired downlink signal, and

$A_{I,FS}$ is the free-space-loss of the interfering downlink signal.

These last two terms were identical in the uplink situation, but are very different in the downlink situation.

C.3 Evaluation of Interference Levels

C.3.1 Uplink Interference from the GSO SPACEWAY Earth Station Into the LEO IRIDIUM Satellite

The uplink interference from the SPACEWAY earth station into the IRIDIUM satellite is determined in Table C-1. In the analysis of this interference mode, the C/I at the IRIDIUM satellite receiver would be unacceptable if the IRIDIUM earth station power level were to be left at the -18.7 dBW level required at the 30° elevation angle without inter-network interference. However, the IRIDIUM earth station has the capability to raise the earth station power level over the range from -22.3 dBW to +12 dBW in the event that the uplink system's C/(N+I) level drops below acceptable levels. It is assumed that this APC servo system would respond rapidly to overcome the increasing interference, up to the limit of + 12 dBW, in the same manner that it would respond to a decrease in C / N due to rain attenuation.

As shown in Table C-1, the IRIDIUM transmitter power level required would depend on the number of SPACEWAY earth station transmitters were operating in the small area covered by the IRIDIUM satellite antenna. This number might be anywhere from 1 to 13. In any case, the APC system in the IRIDIUM earth station could overcome the interference; *it is likely that it could and would do so.*

In conclusion, there would be no harmful interference into the IRIDIUM spacecraft, primarily due to the dynamic use of the APC in the IRIDIUM earth station. However, as seen below, this increase would simultaneously increase interference levels into the SPACEWAY satellite receiver.

C.3.2 Uplink Interference from LEO IRIDIUM the Earth Station Into the GSO SPACEWAY Satellite

The interference into the SPACEWAY satellite receiver is indicated in Table C-2. In this table the IRIDIUM earth station power is shown as a variable, from - 4.8 dBW to + 6.3 dBW. These levels, rather than the level - 18.7 required to overcome only thermal noise, is assumed to be used to overcome interference from the SPACEWAY earth station(s), as discussed in the previous section. The level in the - 10.8 dBW to + 0.3 dBW range would depend on how many SPACEWAY earth terminals were in operation in the uplink antenna beam of the IRIDIUM spacecraft. In any case, the worst-case C/I levels at the SPACEWAY satellite receiver would range from +0.3 dB to - 10.8 dB. Operation of the SPACEWAY system would not be possible in this environment; **the negative C/I margin ranges from - 6.6 dB to a worst-case -17.7 dB.**

It should be noted that these are the margins in the SPACEWAY satellite, and so prohibit operation in the interfered-with bands throughout the complete coverage area of the SPACEWAY uplink beam, not just in a small area near the IRIDIUM earth station.

C.3.3 Downlink Interference from the GSO SPACEWAY Satellite Into a LEO IRIDIUM Earth Station

The worst-case downlink interference from a SPACEWAY satellite into an IRIDIUM earth station is indicated in Table C-3. In determining these interference conditions Equations C-4 to C-6 are used, because the free-space losses are different for transmissions from the two satellites. For this interference mode the worst-case C / I at the IRIDIUM earth station receiver would be -9.6 dB if the APC in the IRIDIUM satellite did not respond to the increase in interference, ie. to a reduction in the downlink C / I. If it did so respond to the maximum output power of the satellite transmitter, it would increase its power level by 15.1 dB to the maximum - 3.2 dBW, resulting in a C / (N+I) of 5.5 dB, only 2.2 dB below its minimum operational level.

This operation of the IRIDIUM APC system in the presence of interference would, however, increase significantly the interference levels in the downlink SPACEWAY receiving earth stations, as indicated in the following section.

C.3.4 Downlink Interference from the LEO IRIDIUM Satellite Into a GSO SPACEWAY Earth Station

The same C-4 to C-6 equations are used to determine the worst-case interference from an IRIDIUM satellite into a SPACEWAY user terminal in the beam of the IRIDIUM downlink beam. Note that 384 kbps traffic is assumed in the SPACEWAY system. If the IRIDIUM system did not implement its APC system on its satellite to overcome interference from the SPACEWAY satellite into its earth terminal, the C/I at the SPACEWAY earth terminal would be an acceptable 10.2 dB. However, if or when the IRIDIUM satellite's APC system was used to the extent possible to overcome interference from the SPACEWAY satellite, the C / I level in the SPACEWAY user terminal would drop to - 4.9 dB, a level 8.8 dB below the minimum that could be accepted in the demodulator of the SPACEWAY user terminal. Assuming that the IRIDIUM system would use its APC to the maximum extent possible, **it must be assumed that the worst-case C / I in the SPACEWAY user terminals would be 8.8 dB below the minimum acceptable level.**

Table C-1

Uplink Interference Into the IRIDIUM Satellite Receiver From One or More SPACEWAY Earth Stations

Parameter	Detailed Consideration	Contribution to C/I Ratio		
Initial Iridium ES Power P_D, dBW	-18.7	-18.7		
Spaceway ES Power P_I , dBW	-3.5	+ 3.5		
Iridium ES Antenna Gain, dBi	56.3	+ 56.3		
Spaceway ES Antenna Gain, dBi	44.3	- 44.3		
Bandwidth of Iridium Signal, MHz	6.25			
Channel Size of Spaceway Signal, MHz	0.500			
Log of No. of Interfering GSO Signals	Max of 13, or 11.1 dB *	0	- 3	- 11.1
Worst-Case C/I		-3.2	-6.2	- 14.3
Required Increase in LEO Power #		10.9	13.9	22.0
Modified Iridium ES Power P_D, dBW to achieve a C/(N+I) of 7.7 dB		- 7.8	- 4.8	+ 3.3

* This 11.1 dB reduction in C/I at the IRIDIUM spacecraft due to multiple SPACEWAY carriers in the IRIDIUM spacecraft antenna beam is a **worst-case value.** It assumes that the 6.25 MHz band is saturated by FDMA uplinks from SPACEWAY Earth terminals, all of them in the small area illuminated by the 5° beam from the IRIDIUM spacecraft. Since the SPACEWAY uplink beam covers a much larger area than the IRIDIUM antenna, this is a very pessimistic number; a more likely number would be 1 or 2 SPACEWAY terminals in operation in the IRIDIUM beam, ie. the F_{BW} factor would more likely be 0 dB or - 3 dB rather than the maximum - 11.1 dB.

\# A total of 30.7 dB of additional APC-controlled power is available to overcome the reduction in power caused by interference from the SPACEWAY earth-station transmissions. The maximum increase required is 22 dB, but a considerably smaller increase is likely required.

Table C-2

Uplink Interference Into the SPACEWAY Satellite Receiver From an IRIDIUM Earth Station with its APC In Operation

Parameter	Detailed Consideration	Contribution to C/I Ratio
Spaceway ES Power P_D, dBW	-3.5	-3.5
Iridium ES Power P_I, dBW	- 4.8 to + 6.3 *	+ 4.8 to - 6.3 *
Spaceway ES Antenna Gain, dBi	44.3	+ 44.3
Iridium ES Antenna Gain, dBi	56.3	- 56.3
Bandwidth of Spaceway Signal, MHz	0.500	
Bandwidth of Iridium Signal, MHz	6.25	
Bandwidth Factor, dB	10.97	+ 10.97
Worst-Case C / I levels		+ 0.3 to - 10.8 *
Margin below Req'd 6.9 dB, in dB		6.6 to 17.7

* The range is dependent on the increase in power that the IRIDIUM earth station implements to control the C / (N+I) level in its satellite. An increase in the APC-controlled IRIDIUM earth station will simultaneously increase the interference level in the SPACEWAY satellite, because the bursts of interference, if they occur, will occur in both satellites at the same time, the time that an earth station of either network is roughly in line with both satellites.

Table C-3

Downlink Interference Into an IRIDIUM Earth Station Receiver From a SPACEWAY Satellite

Parameter	Detailed Consideration	Contribution to C/I Ratio
Initial Iridium Sat. Power P_D, dBW	-18.3	-18.3
Spaceway Sat. Power P_I , dBW	+12.5	- 12.5
Iridium Sat. Antenna Gain, dBi	26.9	+ 26.9
Spaceway Sat. Antenna Gain, dBi	46.5	- 46.5
Bandwidth of Iridium Signal, MHz	6.25	
Bandwidth of Spaceway Signal, MHz	120	
Bandwidth Factor, dB	12.83	+ 12.83
Free-Space Loss, IRIDIUM	182.2	- 182.2
Free-Space Loss, SPACEWAY	210.2	+ 210.2
Initial Worst-Case C/I, dB		-9.6
Increase in Satellite Power Available, dB		15.1
Worst-Case C/I after correction, dB		5.5
C / (N+I) after correction, dB		5.5
Margin below Req'd 7.7 dB, dB		2.2

Table C-4

Downlink Interference Into a SPACEWAY Earth Station Receiver From an IRIDIUM Satellite

Parameter	Detailed Consideration	Contribution to C/I Ratio
Spaceway Sat. Power P_I, dBW	12.5	+ 12.5
Max. Iridium Sat. Power P_D, dBW	-3.2	+ 3.2
Spaceway Sat. Antenna Gain, dBi	46.5	+ 46.5
Iridium Sat. Antenna Gain, dBi	26.9	- 26.9
Bandwidth of Spaceway Signal, MHz	120	
Channel Sep. of Iridium Signals, MHz	7.22	
Bandwidth Factor, dB	12.21	- 12.2
Free-Space Loss, SPACEWAY	210.2	- 210.2
Free-Space Loss, IRIDIUM	182.2	+ 182.2
Worst-Case C/I, dB		- 4.9
Margin below Req'd 3.9 dB, dB		8.8

Annex D

Separation Distances of Earth Stations To Obtain Adequate Isolation Between Networks Through Earth Station Diversity

D.1 Introduction

In this annex the necessary separation distances between Earth stations of the IRIDIUM feeder-link system are determined, such that use of the appropriate Earth station would provide enough isolation between the IRIDIUM and SPACEWAY systems that there would be no harmful interference between them. This is determined for the following two scenarios:

i) when the IRIDIUM system implements its APC system to the full extent to counteract interference from the SPACEWAY system, and

ii) when the IRIDIUM system holds its automatic power control (APC) system in reserve to be used only to counteract atmospheric and rain attenuation.

D.2 Analysis Approach

The starting point of the analysis in this annex is the carrier-to-interference (C / I) equations in Annex C. These equations are generalized to be valid for offset angles of all antennas involved in the process. The resulting equations can be used to determine the necessary angles off boresite of any of the antennas involved to achieve any specified C /I level of either the IRIDIUM or the SPACEWAY system. At that point concentration is placed on the necessary off-boresite angle of the IRIDIUM Earth station, because it is the most directive antenna of either network in the process. Using the known antenna-discrimination characteristics of the IRIDIUM Earth-station antennas, the necessary off-boresite angles θ are determined to protect the IRIDIUM system, and to protect the SPACEWAY system, for each of the two scenarios outlined in the introduction of this annex.

The orbital characteristics of the IRIDIUM and SPACEWAY systems are then used to translate these required angle separations into required distance separations on the ground between the two IRIDIUM Earth stations used in the mitigation process. These results are then generalized to suggest the necessary separation of Earth stations in an IRIDIUM Earth-station complex to allow the mitigation process to be used by IRIDIUM to avoid interference with a number of geostationary (GSO) fixed satellite networks.